REMARKS

Claims 1 through 21 stand rejected. Claim 21 has been cancelled. Claims 1 through 20 remain in the patent application. Claims 1 and 16 are in independent form.

The drawings are objected to as failing to comply with 37 CFR § 1.84(p)(5) because they do not include the reference character 18 for the fastener end. According to Applicant's file, Figure 4 shows reference character 18 pointing to one end of the fastener. Therefore Applicant does not believe that correction to the drawings is required. If Applicant has inadvertently filed a drawing sheet containing Figure 4 that does not include reference character 18, Applicant will immediately produce a replacement sheet therefor.

Claims 1 through 21 stand rejected under 35 USC § 112, first paragraph as failing to comply with an enabling requirement. In particular, the Examiner has questioned what "F_v" physically represents. Applicant has amended paragraph 29 to remove one of the references of F_v from the paragraph to ensure an understanding that F_v is relating to the proofing load of the part being tested. Proofing load is a term known to those skilled in the art. It is synonomous with clamping load. Applicant has submitted herewith three articles that use the term "proofing load" in the regular context of dealing with the subject matter set forth in the above-captioned patent application. Therefore, Applicant respectfully traverses this rejection and hereby asserts that one skilled in the art would be enabled by the specification and the claims of this patent application.

Claims 1 through 21 stand rejected under 35 USC § 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which Applicant regards as the invention. In particular, the Examiner questions what feature makes the "tower" a tower. Applicant identified the structure relating to reference numeral 32 as a tower because it appeared to be a structure that rises above the base in a uniform manner similar to that which a tower may rise above the ground. The tower 32 is higher than the base and the handles extending out from the base. That feature alone would allow someone reviewing the specification and the Figures in the drawings to understand what Applicant is claiming.

Therefore, Applicant respectfully traverses this rejection. If, however, the Examiner believes that there is another word that Applicant could use that would more accurately describe the structure that Applicant refers to as "tower," the Examiner is invited to contact the undersigned to discuss such a global replacement of the word "tower" to a more suitable term.

Claim 9 stands rejected as "said heating rod receptacles" lacks antecedent basis. Applicant has amended claims 9, 10 and 11 to replace the terms "heating rod" with "thermal." This is the term that is used in claim 8 as well as the specification. Therefore, Applicant respectfully traverses this rejection.

The Examiner has rejected claim 16 due to a lack of understanding as to whether the port and key refer to the assembly or the tower. Applicant has inserted punctuation, namely commas, to identify to which structure the port and the key, now the locator pin, belong. Applicant hereby asserts that the port and the locator pin are a part of the tower. Confusion as to use of the term "key" is obviated by amendments to the claims removing this term therefrom and replacing the term "key" with the term "locator pin" as it is used in the specification. The locator pin of claim 17 is the same locator pin of claim 16 and therefore there is no double inclusion.

Claim 16 stands rejected under 35 USC § 103(a) as being unpatentable over United States Patent 4,393,716 in view of 4,603,588. Applicant respectfully traverses this rejection. The '716 reference discloses a fixture for exposing structural materials under a compression load. The '716 reference also discloses a clamping fixture assembly having a body with a defined length and a port for receiving a fastener therein. This reference does not disclose the ability to take measurements of the fastener while it is located within the body.

The '588 discloses a device for gripping specimens having a lateral opening sufficiently large to permit carrying out measurements on the specimen by means of a wire stringing gauge 19 attached to the specimen in known fashion, (column 2, lines 40-42).

Claim 1, as amended to clarify the invention, claims a clamping fixture assembly that is insertable into a tower having a locator pin. The clamping fixture includes a body having a predetermined length, a fastener port disposed at the fastening receiving end for receiving a

fastener therein and an access opening in the body between the head receiving end and the fastener receiving end thereof. The clamping fixture assembly also includes a face plate securable to the head receiving end having a defined roughness. While the '716 reference, in combination with the '588 reference discloses a clamping device having a lateral opening for taking measurements of the specimen therewithin, it does not disclose the use of a plate having a defined roughness to identify and predict the amount of friction disposed between the face plate and the specimen being tested.

In contradistinction, claim 16, as amended, claims a clamping fixture having an access opening and a face plate that is securely bolted to one end of the clamping fixture assembly having a defined roughness. Therefore, it is respectfully submitted that claim 16 and all claims depending therefrom, overcome the rejection under 35 USC § 103(a).

It is respectfully submitted that this patent application is in condition for allowance, which allowance is respectfully solicited. If the Examiner has any questions regarding this amendment or patent application, the Examiner is invited to contact the undersigned.

The Commissioner is hereby authorized to charge any additional fee associated with this Communication to Deposit Account No. 50-1759. A duplicate of this form is attached.

Respectfully submitted,

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Summary Report of the First International Symposium on Strain Gauge Balances and Workshop on AoA/Model Deformation Measurement Techniques

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1. SUMMARY

The first International Symposium on Strain Gauge Balances was sponsored under the auspices of the NASA Langley Research Center (LaRC), Hampton, Virginia during October 22-25, 1996. Held at the LaRC Reid Conference Center, the Symposium provided an open international forum for presentation, discussion, and exchange of technical information among wind tunnel test technique specialists and strain gauge balance designers. The Symposium also served to initiate organized professional activities among the participating and relevant international technical communities.

The program included a panel discussion, technical paper sessions, tours of local facilities, and vendor exhibits. Over 130 delegates were in attendance from 15 countries. A steering committee was formed to plan a second international balance symposium tentatively scheduled to be hosted in the United Kingdom in 1998 or 1999.

The Balance Symposium was followed by the half-day Workshop on Angle of Attack and Model Deformation on the afternoon of October 25. The thrust of the Workshop was to assess the state of the art in angle of attack (AoA) and model deformation measurement techniques and to discuss future developments.

2. INTRODUCTION

The concept of an international strain gauge balance symposium was advocated in a technology assessment entitled "A White Paper on Internal Strain Gauge Balances." This internal document, published by LaRC staff members in March 1995, was based on an international survey of internal strain gauge balances conducted under contract in 1994-1995 (ref. 1). The conclusions of the white paper were presented to a peer review panel on wind tunnel testing technology, composed of selected leaders from major commercial and government aeronautical facilities, held in July 1995 at LaRC. The panel strongly endorsed the proposed international strain gauge balance symposium, which is the first of its kind.

Over 130 delegates from 15 countries were in attendance, including Australia, Canada, China, Finland, France, Germany, India, Indonesia, Israel, the Netherlands, Russia, South Africa, Sweden, United Kingdom, and the United States. The program opened with a panel discussion, followed by technical paper sessions, and guided tours of the National Transonic Facility (NTF) wind tunnel, a local commercial balance fabrication facility, and the LaRC balance calibration laboratory. Vendor exhibits were also available.

The opening panel discussion addressed "Future Trends in Balance Development and Applications." The nine panel members included eminent balance users and designers representing eight organizations and five countries. Formal presentation of papers in technical sessions followed the panel discussion. Forty-six technical papers were presented in 11 technical sessions covering the following areas: calibration, automatic calibration, data reduction, facility reports, design, accuracy and uncertainty analysis, strain gauges, instrumentation, balance design, thermal effects, finite element analysis, applications, and special balances. A general overview of the past several years' activities of the AIAA/GTTC (Ground Testing Techniques Committee) Internal Balance Technology Working Group was presented. The group's activities has prompted sufficient interest among the foreign Symposium attendees, that a separate Euro-Asian Inter-Nation Internal Balance Working Group was contemplated. At the conclusion of the Symposium, a steering committee representing most of the nations and several US organizations attending the Symposium was established to initiate planning for a second international balance symposium, to be held within 2 or 3 years in the UK.

The Workshop on Angle of Attack and Model Deformation Measurement Techniques was held immediately following the Symposium for assessment of the state of the art in AOA and model deformation measurement techniques and to discuss future developments. Twelve presentations from industry and government in the United States, Europe, and Asia covered various AOA and model deformation measurement techniques, applications, and concerns. The Workshop concluded with an open panel discussion.

The following summaries of the panel discussion and selected technical papers were obtained orally and from video tape recordings of the presentations. The authors of this report disclaim responsibility for accuracy of the transcribed notes and regret any misinterpretations of the panelists' and symposium authors' intentions. Panelists and symposium authors should be contacted directly for further elaboration; contact information is available from NASA LaRC representatives.

3. PANEL DISCUSSION

* Co-Chairs of the International Balance Symposium
# Authors of comments on Workshop on AoA/Model Deformation Measurement Techniques

The Symposium opened with a panel discussion entitled "Future Trends in Balance Development and Applications." The panel consisted of the following members:

Ron D. Law, Defense Research Agency (DRA), Bedford, UK, Panel Chair

Maurice Bazin, Office National D'Otudes et de Recherches AJrospatiales (ONERA), France

David M. Cahill, Sverdrup Technology Inc./AEDC Group, USA

Prof. Bernd Ewald, Technische Hochschule Darmstadt (TUD), Germany

Pieter H. Fuykschot, Nationaal Lucht-En Ruimtevaart-laboratorium (NLR), the Netherlands

Steven Hatten, Boeing Commercial Airplane Group, USA

James G. Mitchell, Microcraft, Inc., USA

Lawrence E. Putnam, NASA Langley Research Center (LaRC), USA

Paul W. Roberts, NASA Langley Research Center, USA.

Each panelist briefly presented his views regarding future trends in balance development and applications. Important areas covered included materials, temperature compensation, gauging, analysis methods, and calibration efficiency. The panel members agreed that the existing balance technology will continue to prevail in the foreseeable future, with only evolutionary improvements possible. No radically new basic technologies such as fiber optics techniques are expected to offer any competition in terms of accuracy and reliability. It was agreed that international standards for nomenclature, calibration procedures, accuracy reporting methods, etc. should be adopted in the future following the precedent of the North American Internal Balance Working Group, although agreement is not presently feasible. However, this Symposium is an important first step in establishing formal international discussions about these concerns, especially in regard to agreement on terminology. After the individual presentations a group discussion followed.

Selected observations from the panel discussion follow.

Ron D. Law, DRA Bedford, UK, Panel Chair
Stiffer balances are needed for tests at high angles of incidence under unstable flow conditions. Since the balance forms part of the spring system of the model and its supporting structure, unwanted dynamic oscillations within the balance itself will corrupt test data. Although an infinitely stiff balance would eliminate this problem, it is unrealizable. Stiffer balances are especially needed for half-models and for heavy models. Replacement of strain-gauged flexures with sensitive piezo-electric cells provides greatly increased stiffness with good signal output. The use of high-output platinum strain gauges provides high sensitivity for stiff designs although temperature sensitivity is greater. Composite materials, such as carbon-fiber layered flexures, have been successfully tested in lighter weight balances used for low speed testing. Improved semiconductor strain gauges also offer increased sensitivity. Finite element analysis can be employed during design to predict balance dynamic behavior.

Maurice Bazin, ONERA, France
ONERA has developed balances which provide good drag-count resolution for all wind tunnel applications including cryogenic testing. Future trends are difficult to predict at present. Advanced technology may offer better ways of measuring strain, such as the use of doped materials or micro-laser techniques

David M. Cahill, Sverdrup Technology Inc./AEDC Group.
Analysis of elastic and anelastic hysteresis, and study of fabrication and heat treatment techniques for metallic and non-metallic materials are areas where additional emphasis is needed. Development of alternative techniques for strain measurement would be beneficial. Hardware as well as software compensation techniques for temperature effects are recommended. Calibration techniques need to be examined, including: the number of loadings required for calibration, application of combination loadings including third order and above, and the inclusion of calibration uncertainty analysis. Standardization is needed in the following areas: terminology for forces and moments, and the axis systems; the calibration matrix and the matrix format; treatment of calibration tares; data reduction to forces and moments by the non-iterative mathematical model and the iterative mathematical model; and inclusion of model weight as part of the tares during data reduction.

Prof. Bernd Ewald, TUD, Germany.
TUD has developed a new single-piece balance from copper-beryllium alloy for the European Wind Tunnel (ETW). Although copper-beryllium imposes some inconvenient manufacturing requirements, it is an excellent spring material, has very low hysteresis, and has very high heat conductivity. Tests of titanium alloy at TUD disclosed no detectable hysteresis indicating that it is a promising material for future balance fabrication. Machine calibration is seen as becoming mandatory because of its accuracy and reliability, and because of the excessive manpower requirements for manual calibration. The maximum resolution of the conventional strain gauge is on the order of 25×10^{-9} mm or approximately 1/20000 of the wavelength of visible light. It is unlikely that potential strain measurement alternatives can match this resolution at present. Electric and pneumatic lines bridging the balance in the test model produce measurement bias errors due to unknown residual forces. TUD has considered integrating these lines into the balance structure. The resulting effects of residual forces would then be removed by calibration.

Pieter H. Fuykschot, NLR, the Netherlands.
No major revolution, rather evolution, is seen in balance technology. Two major problem areas are interactions and temperature effects. Balances should be designed for minimum interactions and maximum linearity, rather than using calibration to remove their effects. Nonlinearity can cause bias errors due to rectification effects during dynamic test conditions, which cannot be corrected by calibration. Materials with a low coefficient of thermal expansion, such as titanium, should be considered. Compensation for temperature gradients is important. Balance convection screens can be installed within the model to reduce heat transfer within the flexures. Dynamic modeling should be done during the design phase to minimize resonant vibrations during tests. Standardized model-to-balance couplings should be adopted for inter-laboratory compatibil-

ity. Automatic calibration is an important future trend. The balance should be calibrated through zero load to attain positive and negative loadings rather than by mechanical inversion as usually done during manual calibration. The balance should be calibrated with couplings identical to those used during tests.

Steven Hatten, Boeing Commercial Airplane Group.
Corporate concerns have resulted in an emphasis on reducing the development cycle times for both production aircraft and for test models. Simplified designs and procedures are emphasized, such as parametric spreadsheet design tools. Parametric finite element models are employed to analyze stiffness and dynamic behavior. Older balances in the inventory are being recycled for new testing. External balance calibration is being automated. Balance users at Boeing are demanding improved balance measurement accuracy, especially in drag. Ways to increase drag accuracy are being investigated. Uncertainty due to mechanical hysteresis is being reduced via a redesigned model attachment interface. Effort is also being applied to thermal gradient correction methods for improved accuracy.

James G. Mitchell, Microcraft, Inc.
Progress in strain gauge balances has been slow, with 40-50 year-old strain gauge and design methodology still in use. The strain gauge balance design community should exploit new technology in related fields such as optics, micro-electronics, and smart structures. Balance customers, i.e, test facilities and test engineers, are asking for "better, faster, and cheaper." The response is as follows: Better: Uncertainties can be reduced through study of calibration practices, increased load per unit diameter, increased stiffness, improved math models, and calibration using combined loadings. Faster: While balance design, fabrication, and gauging can be accelerated, the large opportunity is in the area of calibration with automated machines. Balance calibration times are reduced from days and weeks to a few hours. Cheaper: Reduced cycle times result in lower costs.

Lawrence E. Putnam, NASA LaRC, USA.
Comments were made from a wind tunnel user's point of view. LaRC balances must function over test environments ranging from cryogenic conditions at the NTF wind tunnel to high temperatures at the eight-foot high temperature structures tunnel. Drag uncertainty provided by LaRC balances, based on calibration laboratory data, is on the order of 0.6 drag counts, which is adequate for customer requirements. However, operational accuracy in the wind tunnel is worse. Temperature gradients during tests are a major source of uncertainty. Multiple calibrations are needed to estimate precision uncertainties which are not currently done with manual calibration. This is feasible only with automated calibration equipment. Improved balance robustness is needed to reduce down time during tests. Problem areas include strain gauges, cement, and moisture proofing.

Paul W. Roberts, NASA LaRC, USA.
Future improvements in balance design and performance can be expected in a number of areas. Areas in calibration include the experimental design, estimation of separate precision and bias uncertainties, and custom calibration for specific wind tunnel tests. The mathematical model will be extended to include higher order interactions. Although interactions and nonlinearities should be minimized, balance physical size constraints dictated by the test facility may preclude this. More complete uncertainty analysis than is now provided will be available. Real-time compensation for thermal gradients and other effects are being developed. More sensitive strain measurement sensors, although not presently feasible, can be expected over the long term. New fabrication methods with shortened production time are possible. Finally, automatic balance calibration systems are an essential need for the future.

4. OVERVIEW OF TECHNICAL PRESENTATIONS

The majority of the three-and-one-half-day symposium was devoted to 46 papers delivered in 11 technical sessions. A list of the scheduled paper presentations and authors is given in the Appendix. Several papers were not presented due to the authors' inability to attend the Symposium. Brief summaries of selected topics representing important areas of the balance technology are now presented.

4.1 Balance Design

Nearly half of the technical papers presented described unique balance design techniques. Several innovative axial section designs for improved sensitivity and reduced thermal effects were discussed. Finite element analysis methods have disclosed unexpected local stress concentrations, approaching yield limits of the material in some cases, which could not be readily predicted by conventional design methods. Varied techniques for thermal gradient characterization and compensation were described. State-of-the-art methods in strain gauge manufacturing and application were described. Other papers were given on conventional and unique balance applications, including unusual balance designs for special applications.

4.1.1 J. Zhai, TUD, Germany, discussed optimization of internal strain gauge balance design using finite element computation. The aim of the TUD study was to improve accuracy by reducing interferences (interactions) and by increasing stiffness. Sources of linear interactions include the structure, strain gauges, and manufacturing tolerance errors. Strain gauge effects include gauge factor, position, and direction. Product interactions result primarily from deformation of the material. Quadratic and cubic interferences arise from nonlinearity of the material. These effects can be reduced by structural redesign. The linear interaction on drag can be reduced by decreasing the stiffness of the measuring spring, decreasing spacing between measuring beams, and increasing the slope of the main beam. The shape of the drag sensing element can be changed to provide additional decoupling. TUD attained a 38% reduction in drag interaction by choosing suitable dimensions and a 92% reduction in drag interaction by use of a point-symmetrical configuration. Low stiffness causes large nonlinear interactions and a lower natural frequency of the model-balance-sting system which, in turn, increases measurement errors during dynamic test conditions. Stiffness in the X direction was increased 60% by changing the drag-sensing element from a bending beam to a shear spring. Similarly, stiffness in the Z direction was increased 65% by changing the bending moment measuring system from a bending beam to a shear spring. Additionally, stiffness in the Z direction was increased 21% through the use of combined main beams.

4.1.2 Prof. Bernd Evald, TUD, Germany, discussed advanced internal balances for cryogenic and conventional wind tunnels. Only gradual improvements based on careful research and development are anticipated. Three gen-

eral rules for balance users and designers include the following: selection of the load range to match the test requirements as closely as possible; employment of geometric dimensions as large as possible; and design of the balance structure to be as stiff as possible. Three types of balances are generally needed for industrial aircraft development: very sensitive balances for cruise optimization; less sensitive balances for buffet, maximum lift, and dive testing; and an envelope balance for stability and control, control surface deflection, and large AoA and yaw angle tests. Balances with high stiffness are difficult to fabricate with conventional electric-discharge machining techniques. Now, electron beam welding technology gives the balance designer complete freedom to fabricate any desired internal structure. TUD employs an interactive software package for design via fundamental stress and strain analysis methods. Research and optimization are done via FEA software. Maraging steels, which are good for electron beam welding, are used for cryogenic and conventional balances. Special heat treatment methods are applied to reduce hysteresis. Although some authorities advocate the use of heated balances for cryogenic use, Prof. Evald prefers balance designs which tolerate thermal gradients by mechanical cancellation methods and by electrical compensation. He proposes future development of a "black box" plug-and-play balance concept in which all necessary parameters would be stored in a memory chip integrated into the balance structure. The balance identification, calibration matrix, and electrical connection information would be stored on-board. The proper electrical connections and data reduction would be automatically configured by wind tunnel data systems. Future developments would also provide an optical telemetry link from the balance to the wind tunnel data acquisition system to eliminate mechanical bridging caused by strain gauge conductors.

4.1.3 The design philosophy of a high-quality balance at NASA LaRC is briefly presented. All LaRC balances are custom designed to meet the load ranges, physical size, thermal environment, and accuracy requirements for given research projects. Single-piece construction techniques using high-quality maraging steel are employed whenever possible. Most LaRC balances are of the direct-reading type; moment-type balances are typically used in extreme thermal conditions such as the cryogenic environment at the National Transonic Facility (NTF). All LaRC balances employ modulus compensated transducer quality strain gauges. Where extreme thermal environments are anticipated, a patented apparent-strain gauge-matching technique is used. Thermal compensation is provided by pure nickel wire placed in the Wheatstone bridge circuit to reduce temperature effects on the bridge output to less than 0.005 percent full scale per degree Fahrenheit. Balance temperatures and gradients are measured by means of resistance temperature detectors (RTD). These temperature measurements allow linear corrections to be applied for thermal sensitivity shifts and second-order corrections for apparent strain.

4.2 Automatic Balance Calibration

Presentations were given describing four different automatic calibration machines at DRA-Bedford, CARDC, IAI, and TUD. Significant advantages of automatic calibration include manpower savings, decreased calibration time, expanded experimental loading schedules, the ability to apply multiple loadings, and improved calibration accuracy. However, differing results with respect to loading accuracy and repeatability were reported. Primary sources of calibration inaccuracy are load vector misalignment, force measurement sensor inaccuracy, and precise repeatability of the balance mechanical position within test fixtures. Highlights of reported experience with automatic calibration are summarized

4.2.1 *China Aerodynamics Research and Development Center* (CARDC)

CARDC reports the best calibration accuracy although verification data were not available. It is possible that the cited Chinese calibration accuracy is estimated based on the accuracy of the load cells used and the assumption that the system is perfectly realigned after each load application.

4.2.2 *Israel Aircraft Industries* (IAI)

Michael Levkovitch, IAI, gave an unscheduled presentation describing the IAI automatic calibration machine. He indicated that a new machine with a larger load capacity is under development. The presentation indicated that the IAI machine does not reposition to correct loading deflections, but rather measures deflections. Thus, inaccuracies in measurement of angular alignment may dominate the total machine uncertainty. The authors note that since the machine is not designed to function as a repositioning servomechanism, machine accuracy could be improved with better displacement measurement sensors. Without improved positioning measurement accuracy, the use of expensive highly accurate load cells would produce only marginal improvements in overall calibration machine accuracy at present.

4.2.3 *Technische Hochschule Darmst@dt* (TUD)

A first generation automatic calibration machine was designed by TUD and manufactured by Schenk for the European Wind Tunnel (ETW.) A second generation prototype is being developed at TUD. The needs for machine calibration include manpower costs, reduced calibration time, avoidance of human errors, and convenient inclusion of temperature as a calibration parameter. The machine is able to generate loadings in any order in all possible component combinations up to sixth order, thus allowing estimation of third and higher order coefficients. Zero readings are obtained automatically. Loads are generated by actuators and measured independently by load cells, such that the actual applied loads are determined. The balance may be enclosed in a temperature-controlled chamber for cryogenic calibration. The design avoids thermal gradients during temperature-controlled calibration.

4.2.4 *DRA Bedford*

DRA recently developed a six-component precision automatic balance calibration machine for in-house use. Forces are applied using pneumatic actuators and are measured using sensors. Forces are applied such that the need for repositioning is avoided. An example was given of calibration of a balance to be installed away from its virtual center. Since the measured outputs depend on the moment arm length in this configuration, the balance must be calibrated at two positions to permit correction for positioning at any displacement from center during tests. The automatic machine facilitates the multiple calibrations necessary for this application. A second example illustrated static calibration of a dynamic balance by automatic machine where loads must be applied and removed quickly.

4.2.5 *IAI Balance Calibration Consortium*
In 1995 Microcraft established a consortium to calibrate selected balances using the IAI automatic calibration machine at the San Diego, California facility. Two papers related to this effort were given. A paper containing some of the calibration results is summarized in Section 4.3. A summary of the other paper is now presented.

4.2.6 *IAI Machine Calibration of NASA LaRC Balance*
Ping Tcheng, NASA LaRC, presented a comparison of machine calibration accuracy versus manually loaded calibration accuracy. The paper contained a general discussion covering primarily data reduction and uncertainty analysis. Uncertainty analyses of eight sets of machine calibration data indicated that its calibration accuracy is adequate for many applications, providing better than 0.5 percent full-scale accuracy. The authors believe that manual calibration, albeit time consuming and labor intensive, is necessary to attain the best calibration accuracy at present. The IAI machine was user-friendly, easy to operate, with sophisticated supporting software providing immediate data reduction following calibration.

Inconsistencies noted among the eight calibration data sets were traced to poor repeatability of the balance center position caused by slack in the balance-to-test-fixture attachments following removal and re-installation of the balance. It was of interest to note that comments were received describing "spatial relocation error" problems with the Schenk automatic calibration machine at ETW similar to those observed by LaRC during IAI automatic machine calibrations at San Diego.

4.2.7 *Comments by Participants in IAI Calibration Consortium*
Additional comments were received from other Consortium participants regarding the consistencies of the automatic calibration machine. It was agreed by all participants that further improvements would be desirable. Boeing indicated that, in hindsight, a balance with larger interactions should have been selected for test calibration on the IAI machine. This would have better discriminated between the performance of the machine calibration and that of manual calibration. Moreover, the performance of higher order mathematical models and expanded loading schedules could have been better investigated and evaluated. In addition, during the consortium tests, LaRC engineers attempted to evaluate an enhanced calibration experimental design and mathematical model intended for balances experiencing significant third order interactions. Inasmuch as the test balance possessed only second order interaction effects with no apparent third order effects at all, the test of the enhanced calibration design and expanded mathematical model was not well-posed. Therefore, the results were inconclusive.

4.3 Mathematical Modeling
Several presentations covered the interdependent areas of mathematical modeling, calibration experimental design, and calibration uncertainty analysis. It is clear that potentially significant improvements in balance accuracy lie in improved mathematical modeling and in the calibration experimental design. Additional resources may be profitably allocated to further development effort in this area.

4.3.1 Richard S. Crooks, Microcraft San Diego, presented a paper on the limitations of balance calibration mathematical models. This paper, of a general philosophical nature, was illustrated by comparative studies of the robustness, or predictive accuracy, of various polynomial-based mathematical models for three differently sized calibration experimental designs. The calibration data sets were obtained using the IAI automatic machine to calibrate a single balance. It was seen that the largest and most comprehensive experimental design (1322 points) produced the lowest calibration residuals and, consequently, the least overall standard error.

In order to investigate balance model robustness Crooks has taken advantage of the "proof-load" technique. He found that proof-load residuals were significantly reduced by the addition of a single third-order cross-interaction (non-cubic) term to the standard second-order polynomial model. The particular third-order term was selected by trial and error balance coefficient estimation with proof-load test data appended to the normal calibration data set. However replicated calibrations had not yet been conducted to estimate the uncertainty of the significant third-order term and to verify that it is not merely a spurious effect due to random errors, i.e., fitting data to measurement noise.

4.3.2 The authors believe that the practice of attaching proof-load data to calibration data prior to coefficient estimation invalidates subsequent tests for calibration design and model robustness based on proof-load data. Indeed, predictive validation of the model should be based on independent proof-load data acquired at loading combinations and levels absent from the calibration experimental design.

4.4 Uncertainty Analysis
Frank L. Wright, Boeing, discussed how balance accuracy requirements are specified by balance designers and users. In the past accuracy has been imprecisely defined in widely varying ways. Now AGARD Standard 304 is coming into use wherein bias and precision uncertainties, and their combined uncertainty are specified at a given confidence level. The user must clearly state the factors such as test conditions, the coordinate system being used, units, etc. at which the accuracy is being quoted. In the commercial aircraft industry the most important wind tunnel quantity is drag coefficient. Customers now ask for drag count uncertainty at a 95 percent confidence level. Computations for a typical wind tunnel test show that uncertainties of ±0.002° in angle-of attack, ±2.5 lb in normal force, and ±0.8 lb in axial force are necessary to attain this requirement, which is probably not currently possible. Normal force and axial force precision uncertainties during tunnel tests may be estimated from balance calibration data by the following rules of thumb: tunnel repeat-point uncertainty is estimated from repeated back-to-back component calibrations; uncertainty within a Mach number run is estimated from multiple component calibrations interspersed over a five-day calibration; uncertainty over a complete test is estimated from the overall calibration standard error at the desired confidence level; and long term balance bias shift is estimated from zero shifts observed over a four-year period.

John S. Tripp, NASA LaRC, presented an overview of strain gauge balance uncertainty analysis techniques developed at LaRC. A second-order multivariate polynomial direct model is employed; i.e., balance voltage outputs are

represented as functions of the applied input loads in accordance with the physical process being modeled. A Newton-Raphson iterative inversion method is employed for data reduction. The uncertainty analysis employs a global regression technique for least-squares estimation of the polynomial coefficient matrix. Equations are obtained therefrom for computation of calibration confidence intervals and prediction intervals as functions of the applied loadings. This is an extension of the previous method of reporting balance uncertainty as simple percentages of the full scale per component. It is noted that the calibration confidence intervals become fossilized bias errors subsequent to calibration. Additional sources of calibration bias uncertainties include calibration standard errors and mathematical modeling errors. Concepts for selection of calibration experimental design based on analytic methods developed by G. E. P. Box were presented for minimization of overall precision uncertainty and overall bias uncertainty. Statistical techniques for detection and estimation of calibration bias errors have been developed. It was pointed out that present procedures of lumping calibration bias and precision errors together in a single computation may significantly underestimate total calibration uncertainty. If the contributions of highly-correlated systematic errors are additive, then for the large calibration experimental designs typically used for balance calibration the usual RMS standard error underestimates the total uncertainty. Methods for separate estimation of bias and precision uncertainties are being developed.

Mark E. Kammeyer, formerly of the Naval Surface Weapons Center, Dahlgren Division, Silver Spring, MD presented an uncertainty analysis for force testing in production wind tunnels. It is an overview of a complete uncertainty analysis to provide bias and precision limits for computed model attitude and force coefficients inferred from measurements in Hypervelocity Wind Tunnel 9 at Dahlgren. Calibration and measurement uncertainties were propagated through the data reduction equations in accordance with the standard procedures specified by ASME, AIAA, and IOS. A jitter approach using computer software rather than analytical computation was used to propagate the bias and precision limits into the inferred reduced data in order to keep the computational requirements manageable. Results using actual test data show that balance load uncertainties are by far the dominant contributors to overall uncertainties in the reduced parameters. It was also found that precision errors in balance axial force measurements are dominant, whereas bias errors in the other balance components are dominant. These results are helpful in pinpointing areas wherein balance measurement accuracy improvements are needed.

The Dahlgren approach is similar to that reported in an uncertainty study conducted by Batill of Notre Dame (ref. 2) for the NTF wind tunnel in 1993. However, Dahlgren's analysis was more manageable because of the lower complexity of the Dahlgren facility compared to NTF.

4.5 Finite Element Analysis

Three agencies reported activities in finite element analysis (FEA): LaRC, NLR, and TUD. Notable progress in the application of FEA to balance stress analysis has been made recently. The technique is especially suited to determination of stress concentrations, to which conventional stress analysis techniques are not generally applicable. TUD reported using the technique for optimizing stress beam design as described above in Section 4.1.1. The consensus seems to be, however, that FEA is not yet sufficient to replace conventional stress analysis techniques. None of the above agencies report temperature effect analysis using FEA techniques. However, papers have previously been published at ONERA, France, on this topic by Bazin, et al. (ref 3).

Michael C. Lindell, NASA LaRC, presented an FEA study of an existing LaRC cryogenic balance. The purpose was to correlate FEA predicted strain levels with experimental values obtained from loadings, and to identify high-stress concentrations within the balance structure. The FEA software, which is adaptive, does not require prior knowledge of stress concentrations. Strain levels for a single full-scale load in each of the six components were computed and compared with measured values. Differences varied from 0.2% in predicted normal force to 11% in yawing moment. Maximum predicted stress was as large as 40% of yield under a full-scale normal force load, and 50% of yield under a full-scale pitching moment load. The analysis predicted maximum stress on the order of 100% of yield under simultaneous full-scale six-component loading. It was planned to verify this result experimentally. The study concluded that stress levels are predicted accurately by FEA and that stress concentrations can be predicted. Thus, FEA can improve the balance design cycle, and can be used to optimize the design to accommodate higher loads with lower weight and higher safety factors.

4.6 Thermal Gradient Compensation

Maurice Bazin, ONERA, France, discussed methods for balance thermal compensation. ONERA follows multiple approaches, namely bridge resistive compensation, mechanical design to minimize thermal effects, and numerical correction. Mechanical design methods to minimize thermal gradient effects are emphasized since error correction is very difficult compared to error prevention. Design methods to reduce temperature gradient effects include a traction-compression push-pull arrangement and a bending push-pull arrangement. Conventional gauging methods are used.

4.7 Facility Reports

Several presentations provided general descriptions of internal balance development and applications at major facilities.

Henk-Jan Alons, NLR, the Netherlands, gave a presentation co-authored with H. B. Vos describing balance development at NLR. NLR has investigated the performance of model-to-balance and balance-to-sting attachments. A hysteresis angle of 0.01° produces a 0.17% FS error in normal force, which is excessive. In an effort to minimize attachment hysteresis NLR investigated taper joint, cylindrical tap, and end face flange attachments. The hysteresis angle of each of these attachments was measured under load by means of a precision inclinometer. The advantage of the taper joint is its small dimension in comparison to its high bending moment capacity. Its disadvantage is hysteresis under bending due to the unavoidable mating between the sting and the attachment socket. Typical taper joint angle hysteresis of ±0.05° was measured. The cylindrical tap, previously thought to exhibit lower hysteresis, was found to be comparable to the taper joint. The tests disclosed, however, that the end face flange exhibits minimal hysteresis. Currently NLR employs the end face flange on the model end of the balance. Integral Wheat-

stone bridge strain gauges are provided to insure correct installation pre-stress levels. (A taper joint is still employed on the balance sting end to maintain compatibility with existing wind tunnel stings.

5. STATUS REPORT ON NORTH AMERICAN INTERNAL BALANCE USERS WORKING GROUP

David M. Cahill, Sverdrup/AEDC, presented a general overview of the past several years' activities of the AIAA/GTTC Internal Balance Technology Working Group. Numerous areas of progress were cited: an increased willingness to exchange information freely among the participants; a survey of members' balance usage and methods of engineering practice; preliminary agreement on definitions of technical terms; and a 6 × 96 generalized matrix representation of balance calibration parameters. It was noted that a standardized method of computing and reporting balance measurement uncertainties will be developed and accepted soon.

6. FUTURE ACTIVITIES OF THE STRAIN GAUGE BALANCE COMMUNITY

6.1 Second International Symposium on Strain Gauge Balances

A steering committee representing most of the nations and several US organizations attending the Symposium was established to initiate planning for a second international balance symposium. Ron D. Law, DRA-Bedford, announced that DRA might be able to host a second symposium within 3 years. It was agreed that steering committee meetings in the interim should be scheduled in conjunction with other international aerospace conferences to enable as many members as possible to participate. Such an opportunity will arise at the Supersonic Tunnel Association (STA) meeting scheduled to be hosted by ARA and DRA in 1999. It was agreed that Japan should be invited to participate in future symposia. Additional discussion is needed to select a theme for the second Symposium.

6.2 International Round-Robin Balance Calibration

R. W. Galway, National Research Council, Canada, discussed the inter-facility balance calibration project proposed within STA in the fall of 1992. A round-robin test of a single balance by participating facilities had been suggested to provide an opportunity for comparison of different calibration techniques, experimental loading procedures, equipment, data reduction methods, and accuracy reporting methods. It would also provide some insight into the contribution of balance calibration uncertainty in tunnel-to-tunnel comparisons. The round-robin test results would be assembled into a data set to allow investigation of the effects of the various calibration experimental loading designs used by the participants. This data set would be closely controlled in terms of what was measured and how.

STA contains approximately 45 participating organizations of whom about 25 were interested in the round-robin test, and of those about 15 were definitely interested. The Boeing #661 balance had been selected for testing. The STA proposal has remained inactive since the inception of the AIAA/GTTC North American Balance Working Group, the 1995 IAI automatic balance calibration consortium at Microcraft, San Diego, and this Symposium. Galway inquired whether the Symposium delegates considered a round-robin calibration of a single balance to be a "useful exercise." He volunteered to serve as the point of contact through which interested parties may register their interest in participation.

6.3 Euro-Asian Internal Balance Working Group

David M. Cahill proposed the establishment of a separate Euro-Asian Inter-Nation Balance Working Group as a result of interest indicated by several European Symposium attendees in participating in the North American Internal Balance Working Group. He also proposed that the Euro-Asian group should be established under the auspices of AIAA. He suggested that the solidarity of the new group should become established before its eventual merge with the North American Internal Balance Working Group. The feasibility of establishing a Euro-Asian group would depend upon its reception by the proposed membership.

7. CONCLUDING REMARKS ON STRAIN GAUGE BALANCES

The Symposium was very successful in the free open exchange of information, in establishing an international community for future communication on balance usage and technology, and in setting a precedent for future Symposia. It is expected that the professional relationships established during the Symposium pave the way for future international cooperation in the strain gauge balance field. The Symposium provided a previously unavailable technical forum for the exchange of information for users, designers, and manufacturers of strain gauge balances.

The Symposium augmented and extended the results gleaned from the international balance users survey conducted by LaRC in 1995. It is clear that no aerospace agency holds a commanding lead in all technical areas. NASA LaRC is the world's major strain gauge balance user in terms of existing inventory, the number of units used in tests annually, and the number of new balances fabricated annually. Automatic calibration machines, although not yet equivalent to manual calibration with respect to loading accuracy, are an increasingly significant factor in realizing time and manpower savings. They are also an important tool for developing improved mathematical models and calibration experimental designs, and for establishing balance calibration and measurement uncertainties.

Publication of the symposium proceedings is pending.

8. BALANCE SYMPOSIUM REFERENCES

Contractor Reports

1 Kilgore, R. A.: *Internal Strain-Gage Balances: An International Survey.* VigYAN, Inc., Hampton, VA 23666, March 1995.

2 Batill, S. M.: *Experimental Uncertainty and Drag Measurements in the National Transonic Facility.* NASA Contractor Report 4600, June 1994.

Other Reports

3 Bazin, M.; Blanche, C.: and Dupriez, F.: *Instrumentation for Cryogenic Tunnels.* ONERA, France.

9. WORKSHOP ON ANGLE OF ATTACK AND MODEL DEFORMATION

A workshop on angle of attack (AoA) and model deformation measurement techniques was held on the afternoon of the last day of the Symposium. Short review papers were requested covering AoA and model deformation requirements and needs, thoughts for the future, and problem areas, in addition to papers covering actual applications and developments. The thrust of the workshop was to assess the state of the art in AoA and model deformation measurement techniques and discuss future developments in an informal but informative atmosphere. A panel discussion on AoA and model deformation was held in conjunction with the Workshop. Co-chairs of the Workshop were Tom D. Finley and Alpheus W. Burner, NASA LaRC.

9.1 Presentations

Twelve presentations were made at the Workshop. The presenters, affiliation, country, and presentation titles are listed below.

Tom D. Finley, NASA LaRC, USA: "AoA Overview"

Alpheus W. Burner, NASA LaRC, USA: "Model Deformation Overview"

Frank L. Wright, Boeing, USA: "Comparison of Model Attitude systems: Active Target Photogrammetry, Precision Accelerometer, and Laser Interferometry"

Maurice Bazin, ONERA, France: "AoA and Model Deformation at ONERA"

Peter Bauman, DLR, Germany: " DLR Model Deformation Measurement System"

Peiter H. Fuykschot, NLR, the Netherlands: "Vibration Compensation of Gravity Sensing Inclinometers in Wind Tunnels"

J. R. Hooker, McDonnell · Douglas, USA: "Static Aeroelastic Analysis of Transonic Wind Tunnel Models Using Finite Element Methods"

YuFu Liu, CARDC, China: "The Model Real Time Angle of Attitude Measurement in 4m X 3m Low Speed wind Tunnel"

Sergi Fonov, TsAGI, Russia: "Model Deformation Measurements in TsAGI's T-128 Wind Tunnel by Videogrammetry System"

Gregory M. Buck, NASA LaRC, USA: "In-Situ Calibration of Sting Bending Using Optical Measurements"

Anton R. Gorbushin, TsAGI, Russia: "Angular, Linear Model Displacements, and Model Deformation During Wind Tunnel Tests"

Ralph D. Buehrle, NASA LaRC, USA: "Summary of Inertial Model Attitude Correction Techniques"

9.2 Panelists

The panel included the following members:

Frank L. Wright, Boeing, USA, Moderator
Pieter Fuyschot, NLR, the Netherlands
Tom D. Finley, NASA LaRC, USA
Richard A. Wahls, NASA LaRC, USA
Alpheus W. Burner, NASA LaRC, USA
John S. Tripp, NASA LaRC, USA

9.3 Summary of Presentations

Tom D. Finley, NASA LaRC, USA, opened the Workshop with an overview of angle of attack (AoA) measurement. He described the history of AoA measurement at LaRC, which has been based primarily on the use of precision accelerometers. He described the current state of the art of LaRC inertial AoA measurement systems including components and implementation. Specially selected high performance sensors are obtained from the manufacturer. Each unit is packaged with special output temperature compensation circuitry and mechanical isolation pads to reduce the effects of high frequency vibration.

Alpheus W. Burner, NASA LaRC, USA, presented an overview of the development of model deformation measurement capability at the Langley Research Center. Aeroelastic model deformation in wind tunnels was defined. Some fundamental questions and concerns about model deformation measurements in general were presented. The approach, described as a single camera, single view video photogrammetric technique, used to make model deformation measurements at three NASA LaRC facilities, was described. An example of the change in wing twist induced by aerodynamic loading as a function of angle-of-attack at the National Transonic Facility at various dynamic pressures was presented as a typical data example.

Frank L. Wright, Boeing, USA, presented a wind-on comparison among three independent model attitude measurement systems: the traditional inertial accelerometer measurement system, a Boeing designed and built laser interferometer system, and a commercially available photogrammetric system. Test data for the three systems, obtained at various Mach numbers, showed prediction intervals lying between 0.005 and 0.01 degrees. Two other applications of the photogrammetric system were described: flap position measurement during an aircraft flight test, and wing twist measurement of a wind tunnel model

Maurice Bazin, ONERA, France, described developments at ONERA in AoA and model deformation measurement techniques. Precision accelerometers are used for AoA as well as the MAMS system due to Bertin (AGARD VKI-1996) which is somewhat similar to the Boeing Laser Angle of Attack (LAM) system. Potentiometers and encoders are used as well. Model deformation measurements have been made with stereo observation with the RADAC (ONERA T.P. n° 1990-57) and ROHR (ONERA Activities 1996). The RADAC system uses special cameras that contain crossed linear arrays. The ROHR system employs two conventional cameras. The uses of optical fibers and quadrant light detectors and a polarization torsionometer for model attitude and deformation measurements are described in ONERA T.P. n° 1982-91.

Peter Bauman, DLR, Germany, discussed the use of moiré interferometry for the measurement of model deformation and hinge moments. DLR selected moiré interferometry as the technique with greatest potential over others such as coded light, holographic interferometry, and speckle interferometry. The technique currently requires diffusely reflecting surfaces that may necessitate the painting of

highly polished models. Bending and twist measurements have been made in wind tunnels. Expected accuracies are 0.01° for flap angles, 0.03° for twist, and 0.1 mm for bending. Future applications in the automotive industry and for laboratory measurements on helicopter rotor blades are anticipated.

Peiter H. Fuykschot, NLR, the Netherlands, described a correction technique given in a paper presented at an Instrument Society of America conference in May 1996. The technique reduces bias errors in model AoA measurements due to centrifugal forces developed during high tunnel dynamic test conditions. He showed that this inertial error, termed a "sting whip" error, is corrected by measuring the model's linear and angular velocities and multiplying them together. The technique, which requires multiple sensors for correction in both pitch and yaw planes, provides a real-time correction without knowledge of the vibrational modes of the model. He instrumented a model and demonstrated the ability of the technique at two single frequency modes and one multi-frequency mode.

J. R. Hooker, McDonnel-Douglas, USA, discussed the use of experimental measurements to calibrate computational methods used to predict wind tunnel model aeroelastic deformations. A wind-off static loading experiment conducted in the National Transonic Facility (NTF) test section was used to calibrate both the optical technique and the finite element analysis (FEA) technique. Optical wing twist data from the NTF were presented, which were used to calibrate the FEA results with wind on. It was found that one-dimensional FEA analyses are sufficient to generate wind tunnel model jig wing definition, but that advanced three-dimensional solid FEA analyses may be required to generate wing definition suitable for computational fluid dynamic (CFD) analyses. Hooker recommended utilization of CFD methods to define the required accuracy of model deformation measurements for a given configuration and noted that the required accuracy may vary from configuration to configuration. Generally a 5% variation in wing twist is expected to result in acceptable accuracy for low wing transport configurations.

YuFu Liu, CARDC, China, described real-time attitude measurement and side-slip angle measurement systems used in the CARDC 4 by 3 meter low-speed wind tunnel. The pitch measurement system employs a QFlex accelerometer with an added temperature sensor which corrects the accelerometer output as a function of temperature. This system, used over a range from –30 degrees to 110 degrees by offsetting the accelerometer, a provides a measurement precision of 0.005 degrees. The side-slip system employs a laser and dual CCD linear scanning camera to measure yaw from –2.5 degrees to 2.5 degrees with a measurement precision of 0.005 degrees.

Sergi Fonov, TsAGI, Russia, presented examples of wing twist and bending measurements as functions of lift force and AoA at the T-128 wind tunnel using a CCD camera and reference targets with the single camera, single view videometric technique. He also presented results of flap torsion and displacement for which fluorescent strips were illuminated with a nitrogen laser. A prototype deformation measurement system was described for a full-scale helicopter rotor blade using a camera in the rotating hub with connection to the recording system by slip rings. Deformation measurements using projection moiré were also mentioned.

Gregory M. Buck, NASA LaRC, USA, presented results of tests conducted to study sting bending and model injection during wind-on and wind-off conditions at the 20-Inch Mach 6 CF_4 Tunnel. Angle and displacement measurements were made on a small section of the model that was in the field of view of a camera when the model is fully injected into the test section. A back illuminated ground glass view screen was placed in the field of view of the camera to yield a very high contrast edge from which the slope angle and intercept can be found by least squares estimation.

Anton R. Gorbushin, TsAGI, Russia, briefly discussed angle measurements using accelerometers that are manufactured in Russia. He also described a research and development project based on the development of a magnetic system to measure angular and linear model displacements and model deformations during wind tunnel tests. The purpose is to develop a prototype system for the simultaneous measurements of full angular orientation, coordinates, and deformations of a model, including wings, control surfaces, etc., during wind tunnel testing. High-sensitivity three-axis magnetometers on one-domain film structures will serve as transducers for navigation and orientation in an artificial low-frequency electromagnetic field.

Ralph D. Buehrle, NASA LaRC, USA, summarized several sting whip correction techniques proposed over the last few years. Time-domain and frequency-domain methods were not successful in extracting the small signals necessary to determine error. A modal correction technique was tested with limited success. This method requires measurement of all model vibration modes in pitch and yaw prior to wind tunnel testing. The model must be excited in both vertical and lateral directions; modal analysis of the acquired vibration data provides corrective information. During tests corrections at each mode are summed to provide a total correction. This technique requires considerable pre-test and post-test computation. The linear-angular technique of Pieter H. Fuykschot described above has the ability to provide real time corrections without modal analysis.

9.4 Panel Discussion

Frank L. Wright, Boeing, USA, served as panel moderator. He opened the discussion with comments on the need to properly define AoA measurement accuracy requirements. Force measurement using internal strain gauge balances requires accurate AoA measurement to properly resolve normal and axial force to obtain lift and drag forces. However, Wright stressed that AoA measurement accuracy requirements vary depending on the test configuration. For instance AoA accuracy requirements are better defined at cruise conditions and are more stringent for climb-out than for approach conditions. The AoA accuracy requirements at maximum lift are also not well defined. Although ±0.01° AoA accuracy may not be required for every test, better than ±0.1° accuracy is probably always necessary. A comment from the audience noted that the wind tunnel user often requests "the best accuracy you can give me". Wright also stressed that repeatability is of the greatest importance during increment testing at a fixed AoA,. The point was made that the confidence level is often not specified when stating a numerical accuracy requirement.

The topic turned to aeroelastic model deformation. Measurement of aerodynamic twist is needed for comparison with CFD results. As model size increases, wall interference effects become more significant while deformations may increase as well. Both effects must be accounted for. It was asked when ±0.05° experimental wing twist measurement accuracy would be available in wind tunnels. It was pointed out that such measurement accuracies are now possible at the LaRC Unitary Plan Wind Tunnel and are also possible at the NTF wind tunnel at somewhat reduced accuracy. The required accuracy for measurement of the change in wing twist induced by aerodynamic loading is still an open question.

Uncertainty issues in general were then discussed. The uncertainty of CFD results is needed along with the uncertainty of experimental results. The CFD community is just starting to assess uncertainty.

The discussion then returned to AoA where it was stated that AoA should be separated from angle of incidence. To obtain drag, the AoA is needed, not angle of incidence. This led to the question of how well flow angularity can be measured. It was recommended that uncertainty analyses be conducted on the computation of flow angularity from upright and inverted tests. A question was then asked about the Optotrak system in use at Boeing and several other aeronautical establishments. Wright stated that the number of and position of optical markers required for wind tunnel testing with the Optotrak system had not been optimized.

The effect of high-pressure tunnel operation on testing was raised. Wright stated that drag data taken at 4 atm in the NTF wind tunnel was as accurate as data taken at 1 atm in the Boeing wind tunnel; in addition, the 4 atm drag data was as useful for predicting flight behavior as the 1 atm data.

The fragility of precision quartz flexure accelerometers was discussed. Tom D. Finley stated that the typical lifetime of quartz accelerometers is five years. Most problems with accelerometers are due to mishandling rather than excessive model vibration during tests. It was also stated that the quartz flexure is not subject to loss of response as with metal flexures. It was recommended from the audience that accelerometers be powered during transit for protection. Finley pointed out that such protection would occur only in the axial direction. Several people commented that accelerometer manufacturer's specifications are reliable and that they therefore perform no additional calibration. Frank L. Wright stated that accelerometer output data corrected for temperature using manufacturer-furnished data agrees well with temperature-controlled accelerometer output data, as commonly used at the NTF. Pieter H. Fuyschot recommended the use of precision wedges to spot-check angle measurement accuracies. The importance of the use of the local value of the gravitational constant was mentioned.

The discussion turned to the problem of setting the model to zero angle in the facility. Leveling fixtures and tooling balls combined with a bubble level may possibly be used to level horizontal models; however, fundamental leveling problems exist with floor-mounted half models. The importance of the reference surface on which the accelerometer is mounted was also mentioned.

An AGARD uncertainty document published in 1982 was mentioned as an excellent reference. However, Wright cautioned that the individual uncertainty values cited in that reference, which are associated with one drag-count uncertainty, account for the entire one drag-count error. If all of the component uncertainties are combined, approximately 2.8 drag-count uncertainty results as opposed to one drag count.
A member of the audience suspected that load resistor variation caused accelerometer output drift. Finley noted that LaRC employs precision load resistors located in the AoA signal conditioning electronics package rather than resistors installed in the accelerometer package. With this arrangement no significant output drift has been observed.

The panel discussion ended with a brief discussion on the problem of measuring yaw. There appears no clear solution. However, the Optotrak system offers promise in solving the yaw measurement problem.

APPENDIX: STRAIN GAUGE BALANCE PAPER TITLES AND AUTHORS

Authors	Title	Organization
Session 1 CALIBRATION & DATA REDUCTION		
V. Crivoruchenko & I. Panchenko	Calibration of Multi-Component Aerohydrodynamic Balances with Application of Optimal Planning Tests Methods	TsAGI, Russia
M. Quade & K. Hufnagel	The Development of a Modern Manual Calibration and Measuring System for Internal Balances	Technical University of Darmstadt, Germany
I. N. Panchenko	Transformation of Aerodynamic Balances Formulas to the Resolved Respecting To Loading Form	TsAGI, Russia
R. S. Crooks	Limitations of Internal Balance Calibration Math Models for Simulating Multicomponent Interactions	Micro Craft Technology, San Diego, USA
Session 2 FACILITY REPORTS		
E. Graewe, B. Ewald, & D. Eckert	Design and Development of Internal Balances for the German/Netherlands Low Speed Wind Tunnel (DNW)	Technical University of Darmstadt, Germany
D. X. He, & X. R. Gu	Recent Advances in Strain-gage Balances at CARDC	CARDC, China
D. Cahill	AIAA/GTTC Internal Balance Technology Working Group	Sverdrup/AEDC,USA
H. B. Vos	Strain Gauge Balance Development at NLR	NLR, the Netherlands
P. W. Roberts	NASA LaRC Force and Strain Measurement Capabilities	NASA LaRC, USA
Session 3 SPECIAL BALANCES I		
B. Ewald, K. Hufnagel, G. Viehweger & R. Rebstock	The Half Model Balance for the Cologne Cryogenic Low Speed Tunnel (KKK)	Technical University of Darmstadt, Germany
K., Fristedt	Internal Bending Beam Strain-Gauge Wind-Tunnel Balances	AKTIEBOLAGET ROLLAB, Sweden
K. K. Guo	Hinge Moment Balance for Complete Models	Beijing Institute of Aerodynamics, China
A. Kuzin, G. Shapovalov, & N. Prohorov,	Strain-Gage Balance for Magnetic Suspension and Balance System	Moscow Aviation Technological Institute, Russia
Session 4 ACCURACY AND UNCERTAINTY ANALYSIS		
A. J. Day, & N. Corby	Developments to Improve the Accuracy of Half-Model Balance Measurements in the AEA 9ft x 8ft Transonic Wind Tunnel	Aircraft Research Association, Ltd., UK
P. H. Fuykschot	Looking for the Last Drag Count: Model Vibrations Vs Drag Accuracy	NLR, the Netherlands
M. E. Kammeyer	Uncertainty Analysis for Force Testing in Production Wind Tunnels	Naval Surface Weapons Center, USA
F. L. Wright	Experiences Relative to the Interaction Between the Balance Engineer and the Project Engineer with Regard to Measurement Uncertainty	Boeing Commercial Airplane Group, USA
J. S. Tripp	Strain Gauge Balance Uncertainty Analysis at NASA Langley - A Technical Overview	NASA LaRC, USA
Session 5 AUTOMATIC CALIBRATION		
Ewald K., Hufnagel, L. Polansky, & L. Badet	Development and Construction of Fully Automatic Calibration Machines for Internal Balances	Technical University of Darmstadt, Germany
R. D. Law	The Application of an Automatic Precision Balance Calibration Machine to the Calibration of Wind Tunnel Strain-gauged Balances	DRA-Bedford, UK
Y. P. Zhang	Fully Automatic Calibration System of the Six Component Balance for High Speed Wind Tunnels.	CARDC, China
P. Tcheng & J. S. Tripp	Statistical Analysis of the NASA LaRC Evaluation of the IAI Automatic Balance Calibration Machine	NASA LaRC, USA
Session 6 APPLICATIONS		

Authors	Title	Organization
D. Booth	Development of a Six Component Unitized Flexured Force Balance	Micro Craft Technology, USA
V. Lapygin	Typical Balance Test tasks for Aerodynamic Facilities of TSNIIMASH	TSNIIMASH, Russia
D. Levin & M. Ringel	Accurate Axial Force Measurement with Small Diameter Balances under High Normal Loads	Technion, Israel
A. R. Gorbushin	Some Peculiarities of Balance Tests in the Transonic TsAGI T-128 Wind Tunnel	TsAGI, Russia
T. C. Moore	Strain Gages in Service at NASA Langley - A Technical Review	NASA LaRC, USA
Session 7 SPECIAL BALANCES II		
L. X. Liao & Y. Tao	A Water-cooled Six-Component Internal Balance	Beijing Institute of Aerodynamics, China
G. S. Liu, Z. G. Lu, & X. Q. Qi	Single Load and Multicomponent Balance Calibration System (SL&MBCS) of Piezoelectric Balance in Shock Tunnel	CARDC, China
P. Parker	Free Oscillation Dynamic Stability Balance System	Modern Machine & Tool Company Inc., USA
Session 8 BALANCE DESIGN		
G. Drouin, B. Girard, & K. Mackay	A Stiff Monopiece Wind Tunnel Balance	Defence Research Establishment, Canada
G. I. Johnson	A New Master Balance for the MK15 Calibration Rig at FFA	FFA, Sweden
N. R. Patel	Development of A Five-Component Balance As an Integral Part of a Control Surface	Modern Machine & Tool Company Inc., USA
M. A. Ramaswamy	Design Features of Some Special Strain Gage Balance	India Institute of Science, India
R. D. Rhew	NASA LaRC Strain Gage Balance Design Concepts	NASA LaRC, USA
Session 9 INSTRUMENTATION, STRAIN GAUGES, & THERMAL EFFECTS		
B. Fagerstrom & P. Kemppainen	An Easy-to-use Calibration and Readout System for Small Internal Beam-Type Wind Tunnel Balances	Helsinki University of Technology, Finland
X. R. Gu & J. Q. Hu	Development of BFH-series Strain Gages	CARDC, China
A. T. Ferris	Strain Gauge Balance Calibration and Data Reduction at NASA Langley Research Center	NASA LaRC, USA
W. Liu	Temperature Effect Research on Strain-gage Balances in a Conventional Wind Tunnel	CARDC, China
M. Bazin	ONERA Balances and Dynamometers	ONERA, France
Session 10 FINITE ELEMENT ANALYSIS & NEW TECHNOLOGY		
M. Lindell	Finite Element Analysis of a NASA National Transonic Facility Wind Tunnel Balance	NASA LaRC, USA
J. Zhai & K. Hufnagel	Optimization of the Internal Strain Balances with Finite Elements Computation	Technical University of Darmstadt, Germany
V. Lagutin	New Design of Tubular Type Strain-gage Balances	TSNIIMASH, Russia
B. Ewald, K. Hufnagel, & E. Graewe	The Development of Advanced Internal Balances for Cryogenic and Conventional Tunnels	Technical University of Darmstadt, Germany
V. Bogadanov & V. S. Volobuev	The Status and Prospects for the Further Development of Load Measuring Devices for Wind Tunnel Tests	TsAGI, Russia
Session 11 SPECIAL BALANCES III		
G. Rajendra, H. S. Murthy, & G. V. Kumar	A New Balance Calibration Methodology for Long Slendered Bodies in a Blowdown Tunne	National Aerospace Laboratories, India
C. J. Suarez, & G. N. Malcolm	Development of a 5-component Strain Gage Balance for Water Tunnel Application	Edidetics Corporation, USA
Z. G. Tang	Development of Microbalance in Low Density Wind Tunnel	CARDC, China
B. Vasudevan & M. A. Ramaswamy	Novel Oil Filled Bellow Type Internal Strain Gauge Balance for Water Tunnel Applications	India Institute of Science, India

About the Author/BENGT BLENDULF

Bengt Blenduif is the president of Clemson EduPro, Inc. and is a professional educator specializing in fastener engineering education. Bengt's involvement in fastening technology goes back to 1966 when he joined one of the leading European fastener manufacturers. He has been in the mechanical/ metalworking field since 1961. Educated in mechanical engineering in Sweden, he moved to the United States in 1974 to start a subsidiary for a Swedish fastener manufacturer. Bengt also served for 8 years on the faculty in the College of Engineering and Science at Clemson University. Since 1997 he (Clemson EduPro, Inc.) teaches highly rated courses in Fastening Technology and Bolted/Screwed Joint Design in the U.S., Canada, and Mexico, primarily for engineers, but also for other fastener professionals. Bengt serves as chairman of the Bolting Technology Council and is the author of an extensive lecture book as well as over 80 technical papers and articles related to fasteners and international standardization. Bengt's business address is: Clemson EduPro, Inc., PO Box 1862, Clemson, SC 29633-1862; phone/fax 864-654-1126; e-mail: edupro@carol.net, website: wwwedupro.us.

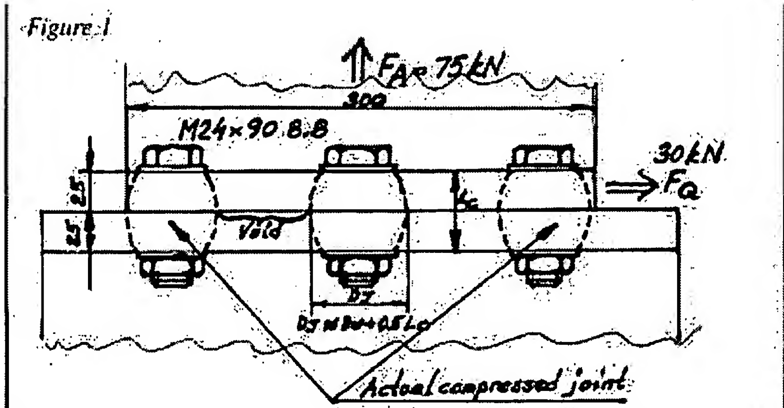
Big Bolts Better?

Choices for Performance and Economy

Few fastener engineers had a better understanding of bolted/screwed joint economy and performance than my mentor and teacher in fastening technology, Carl Dock of Sweden. Unfortunately, Carl passed away earlier this year and will be greatly missed on both sides of the Atlantic as a great person and fastener expert in ISO and many other areas. Carl developed the IPC concept (In-Place-Cost) that takes into account all aspects of a joint, such as drilling, tapping, purchasing, inventory keeping, handling, assembly, drive systems and other related issues. From this concept, many new fasteners have been developed, particularly in the area of thread rolling screws, screws and nuts with captive components (i.e. Sems) drilling screws, etc.

This section will look at ways of optimizing a joint system in order to find the best solution based on performance and economy. In Figure 1 we have details of a machine using 3 M24x90 8.8 bolts, Class 8 nuts and hard washers (HRC2O mm) to connect two parts with external loads going in both axial and transverse directions. The axial load F_A, 75 kN (approx. 17 000 lbf), and the transverse load F_Q, 30 kN (approx. 6 750 lbf), are carried by the 3 M24 bolts. This is the worst-case scenario for bolted joints; side loads are very tricky to deal with if we wish to have a frictional hold rather than a pure shear joint (which is a lot easier to design). This is particularly true when we also have an axial component trying to separate the clamped parts, thereby decreasing the pressure in the parting plane.

Figure 1



By using the 3 "big" bolts we are able to carry the two loads (F_A and F_Q), but if we look at the loading plane we find that the actual joint areas between the two joined plates are somewhat limited. A good approximation of the actual joint area diameter, having two plates of the same thickness, is to add the bearing surface diameter of the bolt head or nut face (D_W) and the thickness of one of the plates (or $D_W + 0.5L_C$, where L_C is total clamping length). In our case we have voids in the load distribution, and those voids will not help in preventing slipping between the two planes. I have used the design guideline VDI 2230 (German Engineering Society) to calculate and verify this joint and SR1 (a software based on VDI 2230) for the optimizations. VDI 2230 is, in my opinion, the most sophisticated calculation base for highly stressed bolt joints in existence today. In my engineering classes (Fastening Technology and Bolted/ Screwed Joint Design) I use the VDI approach since it is much superior to materials in our current college textbooks. The first edition was issued in 1976 and the latest edition in February 2003.

Figure 2 is a principal printout of one of the bolt locations, where the total loads have been divided by 3 (the number of bolts). Even with the VDI and SR1 we still have to break down a multiple axes joint into single axis bolt locations. I have written some explanatory notes on the table drawings in this chapter to familiarize you with some of the terms (abbreviations are from German). In this case we are using 90% of the bolts yield capacity, which is right at the proof load level (stress under proofing load). The Rp0.2 and proof load have been adjusted to take the torsional effect (thread friction during tightening) into account.

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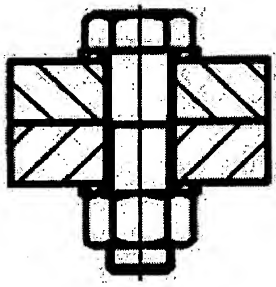
BIG BOLTS, *from page 8*

Figure 2



ISO 4014 - M24 x 90 - 8.8 SW36 WAF				
	OD	ID	thick.	
i	da	di	l	material
1	45.0	25.0	4.0	AISI 1045 HEAT TR. Min HRC30
2	100.0	26.0	25.0	AISI 1018
3	100.0	26.0	25.0	AISI 1018
4	45.0	25.0	4.0	AISI 1045 HEAT TR. HRC30

Washer

Washer

bolted joint with nut (DSV)		
ANSI 1 - SW 36 WAF		
h M	mm	21.5

Company X
Clemson Edu/Pro/Blandull

Using 90% of reduced Rp 0.2

Tightening factor

LOAD (T=20°C)		
FA max	N	25000
FA min	N	0
FQ	N	10000
FKrequ,herd	N	85000
FK min	N	86254
FM-Rp	N	167098
FM,max	N	168360
FMmax,req	N	166374
FMmin,req	N	103884
fz	mm	0.0195
Fz	N	14941
FV min,req	N	89043
FV min	N	80296
FV max	N	153439
FSA max	N	957.1
FPA max	N	24043
F Rm	N	262576
F Rp	N	232653

Axial load

Transverse Clamping

— " —

Relaxation

ASSEMBLY (Nut driven)		
nue Rp		0.90
alpha A		1.80
MA max/min	Nm	775.3 / 484.5
alpha max/min	deg	25.37 / 18.48

FRICTION	min	max
μG thread	0.140	0.140
μK bearing	0.160	0.160
μTr plates	0.160	0.160
K factor	0.191	"nut factor"

FACTORS OF SAFETY (T=20°C)		
safety against loosening	FM,max/FMmax,req	1.01
safety yield point red.B	SF=Rp/Sig,redB	1.29
safety ag.fatigue fract.(concen.)	SD=Sig.AS/Sig.a	30.24
safety plate surface pressure	Sp=pG/pmax	1.65
safety against slipping due to FQ	SG=FKmin/FKQreq	1.06

2!

2!

Load going to bolt
Load going to plates } *from F_A*

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BIG BOLTS, *from page 178*

All safety factors are above 1, which is normally acceptable, two are dangerously close, namely 1.01 against risk of coming loose and 1.06 against possibility of slipping. Since the latter is crucial to this design (with a side load of 309 kN) we may consider a redesign to improve these numbers. To go higher than 90% of Rp0.2 (yield) is risky business with a torque wrench, however well calibrated (it will still cause a typical tension scatter of ±23% alpha A=1.6). The alpha A factor is the ratio between the highest assembly load and the lowest caused by the relative inaccuracy of the tightening equipment. Therefore, a designer would likely think in terms of bigger bolts. The next larger standard size is M27, so let's see what difference that would make for this joint.

M27×90 8.8 (3 bolts)

LOAD (T=20°C)		
FA max	N	26000
FA min	N	0
FQ	N	10300
FQreq	N	65000
FK min	N	81002
FM Rp	N	246419
FM max	N	197133
FMmax,req	N	171530
FMmin,req	N	107206
fz	mm	0.0195
Fz	N	18106
FV min,req	N	89041
FV min	N	108044
FV max	N	178909
FSA max	N	906.6
FPA max	N	24041
F Rm	N	337307
F Rp	N	302200

ASSEMBLY (Nut driven)		
nue Rp		0.80
alpha A		1.60
MA max/min	Nm	1017 / 633.6
alpha max/min	deg	25.30 / 15.67

FRICTION	min	max
µG	0.140	0.140
µK	0.160	0.160
µTr	0.160	0.160
K	0.191	

FACTORS OF SAFETY (T=20°C)		
safety against loosening	FM,zul/FMmax,req	1.15
safety yield point red.B	SF=Rp/Sig red.B	1.44
safety ag.fatigue fract.(concen.)	SD=Sig,AS/Sig,a	33.21
safety plate surface pressure	Sp=pG/pmax	1.83
safety against slipping due to FQ	SG=FKmin/FKQreq	1.30

Figure 3

Costs more than 2x!

In this case we are backing off to using 80% of yield since we can produce a residual clamping force FKmin of 81002 N, only needing about 65000 N. This alternative gives us good safety factors, but at the expense of cost. Using list prices from a 1998 catalog, the cost of the M24 example with 3 bolts M24x90, 3 M24 nuts and 6 hardened washers would be **$26.70**. With the M27 alternative the cost will more than double to **$68.49**! Not a very good prospect when everybody is pressured to play it economical (or even cheap). Add to that the cost of larger size holes to drill and much higher torque values. From an IPC standpoint, this is not a desirable direction to go.

Company X

Clemson BoltPro/Bond.tl

M20×80 8.8 (5 bolts)

LOAD (T=20°C)		
FA max	N	15000
FA min	N	0
FQ	N	6000
FKreq	N	40000
FK min	N	53843
FM Rp	N	141302
FM max	N	127172
FMmax,req	N	106094
FMmin,req	N	88640
fz	mm	0.0196
Fz	N	11107
FV min,req	N	54473
FV min	N	68316
FV max	N	116008
FSA max	N	527
FPA max	N	14473
F Rm	N	203179
F Rp	N	181684

ASSEMBLY (Nut driven)		
nue Rp		0.80
alpha A		1.60
MA max/min	Nm	491.5 / 307.2
alpha max/min	deg	31.98 / 19.99

FRICTION	min	max
µG	0.140	0.140
µK	0.160	0.160
µTr	0.160	0.160
K	0.193	

FACTORS OF SAFETY (T=20°C)		
safety against loosening	FM,zul/FMmax,req	1.21
safety yield point red.B	SF=Rp/Sig red.B	1.10
safety ag.fatigue fract.(concen.)	SD=Sig,AS/Sig,a	38.10
safety plate surface pressure	Sp=pG/pmax	1.20
safety against slipping due to FQ	SG=FKmin/FKQreq	1.44

Figure 4

Good safety factors.
Cost = M24 alternative

Since this design leaves rather big distances between the bolts (when using 3) and uneven clamping on the total joined surface, we may want to try to use *more and smaller bolts*. Our next option could be to use 5 M20x80 8.8 bolts with nuts and hard washers. We can use 10 mm shorter bolts, since nuts and washers are a little thinner. As we can see in the safety factor table in Figure 4, we have as good or better result with 5 M20 bolts as we had on 3 M27 bolts. Also, the cost for this alternative with 5 M20x80 bolts, 5 M20 nuts and 10 hard washers is **$24.70** or about the same as for the original M24 alternative. So, smaller is often a better solution than going bigger! Of course, there will be 2 more holes to drill and 2 more nuts to tighten, but since they are also smaller it will not be that much of a difference. The IPC (In-Place-Cost) will not change very much, but the quality of the joint will be vastly improved.

When we are on the roll of optimizing this joint, let's find a way of engaging the entire "stretch or row" of fasteners so that we have a better, continuous pattern for the frictional hold. We could look at the bridge builders and steel contractors for some principal approaches to this. Next time you drive past a bridge, take a look at the tight bolting pattern used to connect the beams for the span. *But keep your eyes on the road so you don't run into the bridge!*)

This technique, with a close bolt pattern, develops a large friction surface, which will help the joint to stay close even when high transverse loads act on the bolted joints in the bridge span. If we "mimic" this approach for our mechanical joint, we can perhaps go one step further and use M16 fasteners. Let's see how this would work. (See Figure 5.)

Using the SR1 software I was able to carry out a variety of options for M16 fasteners relatively quickly. The best alternative proved to be using 6 M16 bolts in Class 10.9 (Figure 5). Since the machinery is to be used indoors, we did not need, for corrosion protection, any other surface treatment than the phos/oil that we usually get on these i 0.9 (Grade 8) products. Also, because of the strength of the material, only 75% of Rp0.2 (yield) is necessary for the preloading., As you can see in the safety factor table, we have almost as good values as we had for M20 and M27, and *a lot better* than the original M24 design. And the best part of all, the cost for 6 bolts, 6 nuts and 12 hard washers is now only **$14.70**, or about half of the original design. Even with more holes to be drilled and more (but smaller) fasteners to be tightened, this may be the lowest IPC of all the alternatives discussed here. With a mean torque of 243 Nm (179 lb ft) instead of 630 Nm (465 lb ft) it will be a lot easier to tighten these M16 fasteners using smaller torque wrenches and improving the ergonomics.

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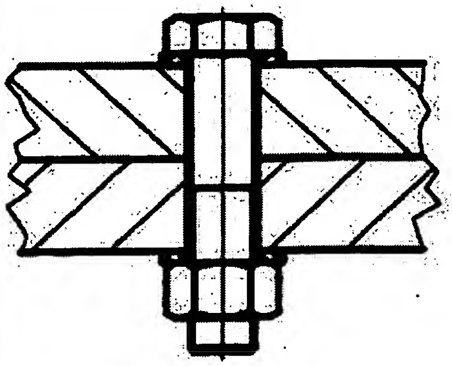
Figure 5



ISO 4014 - M16 x 80 - 10.9 SW24				

i	da	di	l	material
1	30.0	17.0	3.0	AISI 1045 HEAT TR.
2	100.0	17.5	25.0	AISI 1018
3	100.0	17.5	25.0	AISI 1018
4	30.0	17.0	3.0	AISI 1045 HEAT TR.

bolted joint with nut (DSV)		
ANSI 1 - SW 24		
h M	mm	14.8

This would be my choice for this joint.

Company X
Clemson EduPro/Blendulf

LOAD (T=20°C)		
FA max	N	12500
FA min	N	0
FQ	N	6000
FKreq	N	32000
FK min	N	40342
FM-Rp	N	128789
FM,max	N	96599
FMmax,req	N	83252
FMmin,req	N	52032
fz	mm	0.0195
Fz	N	7958
FV min,req	N	44076
FV min	N	52419
FV max	N	88644
FSA max	N	423.6
FPA max	N	12076
F Rm	N	162936
F Rp	N	147268

180 *THE DISTRIBUTOR'S LINK*
BIG BOLTS, *from page 178*

MA max/min	Nm	299.2 / 187
alpha max/min	deg	42.62 / 26.84

FRICTION	min	max
μG	0.140	0.140
μK	0.160	0.160
μTr	0.160	0.160
K	0.193	

FACTORS OF SAFETY (T=20°C)		
safety against loosening	FM,max/FMmax,req	1.16
safety yield point red.B	SF=Rp/Sig.redB	1.42
safety ag.fatigue fract.(concen.)	SD=Sig.AS/Sig.a	32.28
safety plate surface pressure	Sp=pG/pmax	1.23
safety against slipping due to FQ	SG=FKmin/FKQreq	1.29

Good safety factors.
Low cost of fasteners.
Low IPS!

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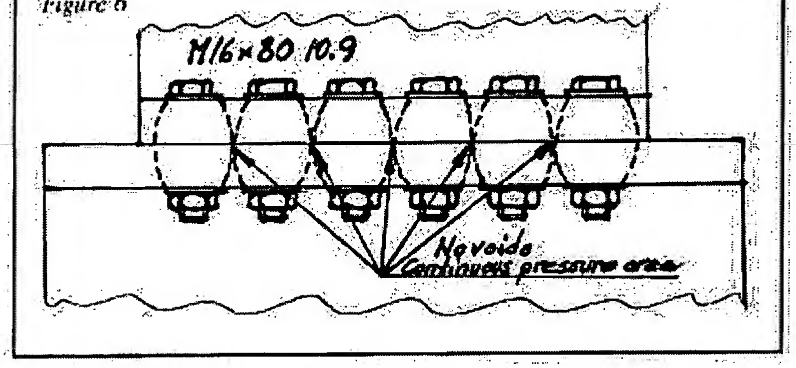
BIG BOLTS, *from page 184*

In figure 6 we can also see how the clamped "bodies" are developing a continuous pressure area, taking advantage of the better frictional hold we get with better spacing. This tight pattern is an absolute necessity if a joint is gasketed, because voids in the parting planes can cause leaks to develop. Gasket pressure should be kept uniform. There are a couple of other advantages to using smaller fasteners. The ratio between the diameter of the fastener and the clamping length is larger, which gives us more favorable elasticity signature of the joint (stiffer joint, springier fastener). Therefore, more of the external, axial load F_A will be absorbed by the compressive energy in the joint and less will go to the pre-loaded fasteners due to increased diameter to clamping length (d/L_C) ratio. Additionally, the endurance (fatigue) limits for smaller fasteners are higher per thread stress area unit than for larger diameter fasteners, which could be very important if external loads are cyclic/alternating.

Figure 6



The major lessons we have learned from optimizing the joint as we have done above is basically:

1. Bigger is not always better.
2. The geometry of the joint should be taken into account for best joint elasticity signature.
3. Transverse or combined loads require a lot more preload than pure axial loads.

The VDI 2230 Guideline

If we had calculated the joint alternatives discussed above by hand following the VDI 2230 it would have taken many hours because of the complexity of the mathematics and the many variables included. Having said that, the fact of the matter is that a highly stressed bolted/screwed joint is most often very difficult to design, particularly if "overdesign" is not an option due to economics and other restraints. For the serious design engineer involved in highly stressed bolted/screwed joint design, having access to the VDI 2230 Guideline is something I always recommend my students. It is now also issued as a German/English version (February 2003), which, of course, makes it a lot more accessible to the engineer in the U.S. It can be obtained from the publisher of all VDI guildelines:

Beuth Verlag GmbH
Burggrafenstrasse 6
D-10787 Berlin
Germany
Web: www.beuth.de

Software Version SR1

A very convenient way of making quick calculations of options can be found in SR1, a software program that contains not only the VDI 2230, but also other important data. It was developed by Ralph Shoberg of RS Technologies in Farmington Hills, MI in cooperation with Fritz Ruoss, a programming expert from Hexagon Software in Germany. With SRi we are able to analyze and verify our bolted joints more easily and accurately. This software can be obtained from:

RS Technologies
24350 Indoplex Circle
Farmington Hills, MI 48335
Phone 248-888-8260
Web: ww.rstechltd.com

Before we start using computer programs, however, we must fully understand what kind of "numbers" we are entering. No software in this design area will "think" for us. It will, however, speed up the verification of the designer's intentions and give us opportunities to quickly develop alternative solutions. The same thing applies to FEA (Finite Element Analysis) used by many engineers/designers today. Although very sophisticated, FEA does not design for us, but if properly used it give us very valuable guidance in our own decision making process.

In closing, big is not always better. Lean, mean and flexibility usually wins!

Specification

for

GALVANIZED STEEL BOLTS AND NUTS / WASHERS

CEB Standard 064 - 1 : 1999

CEYLON ELECTRICITY BOARD

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CONTENTS

SPECIFICATION FOR GALVANIZED STEEL BOLTS AND NUTS / WASHERS

1.0 SCOPE

This specification covers the general requirements of manufacture and testing of Galvanized Steel Bolts, Nuts and Washers for use in the overhead power distribution lines

2.0 APPLICABLE STANDARDS

The items and components supplied shall be in accordance with the standard specified below or later editions and/or amendments thereof.

a)	ISO 898		-	Mechanical properties of fasteners
	Part – 1-	1988	-	Bolts, screws and studs
	Part – 20	1992	-	Nuts with specified proof load values Coarse thread
b)	ISO 261 -	1981	-	ISO general purpose Metric Screw Threads – Selected sizes for screws, bolts and nuts
	ISO 965		-	General purpose metric screw threads
	Part – 2 -	1980	-	Tolerance – Limits of sizes for general Purpose bolts and nut threads.
c)	ISO 887 -	1983	-	Plain Washers for metric bolts screws and nuts
d)	ISO 4759 -	1991	-	Tolerance for fasteners and washers
e)	BS 729 -	1971	-	Hot Dip Galvanized Coatings on Iron and Steel Articles

3.0 BASIC FEATURES

3.1 General

The galvanized steel bolts and nuts shall be of the hexagonal heads type as per ISO 898 Part 1&2 and the screwed threads shall comply with ISO 261. The mechanical properties of the bolts and nuts shall comply with ISO 898 and shall be hot dip galvanized conforming to BS 729.

3.2 Material

The steel used for the manufacture of the bolts and nuts shall be such that the mechanical properties of the finished products shall not be less than that of Property Class 5.6 as stipulated in Table 3 of 898-1.

3.3 Hexagonal Head

The hexagonal head of the bolt shall be formed by cold forging and the required marking shall also be formed (embossed) during the formed (embossed) during the forging operation.

3.4 Screw Threads

The bolts shall be provided with rolled threads and the form of thread, diameters and associated pitches shall be in accordance with ISO 262.

3.5 Nuts

The height and width across flats of the hexagonal nuts shall be as stipulated for Style 1 in Table A.3 of ISO 898-2. The property class shall be marked as per ISO 898-2

3.6 Chamfering and Facing

i) Head of Bolts

The hexagon bolt heads shall be chamfered at an angle of approximately 30 degrees on the upper faces. The diameter of the ring formed by the chamfer on the upper face of the bolt shall not be smaller than 90% of the minimum across flat dimension.

ii) Ends of Bolts

The thread rolling operation shall provide the necessary chamfer to the end of the bolt, and the end shall be reasonably square with the centre line of the shank.

iii) Nuts

The nuts shall be chamfered at an angle of approximately 30°C on one face and they shall be machined on both faces

3.7 Diameter of Shank of Bolts

The diameter of the unthreaded portion of the shank of Bolts shall be in accordance with the standard specified and it shall be round and uniform.

3.8 Length of Bolts and thread length

The nominal length and the thread length of various sizes of bolts shall be as given below;

	Bolt Diameter	Bolt Length	Thread Length
a)	12mm	90mm	25mm
b)	12mm	120mm	75mm
c)	16mm	50mm	25mm
d)	16mm	120mm	25mm
e)	16mm	180mm	75mm
f)	16mm	200mm	75mm
g)	16mm	230mm	75mm
h)	16mm	250mm	75mm
i)	16mm	280mm	75mm
j)	16mm	300mm	25mm
k)	16mm	360mm	25mm

3.9 Plain Washers

The washers shall be of the flat round type and shall be in accordance with SIO 887 1983 and hot dip galvanizes as per BS 729. The thickness shall not be less than 3.0mm and the diameter shall not be less than be 45mm with a centre hole to allow M12 / M16 Bolt (as per schedule of prices) to pass through.

3.10 Spring Washers

The spring washers shall be of single coil, rectangular cross section conforming to BS 4464 and shall be hot dip galvanized as per BS 729. The Thickness shall not be less than 3.3mm and the diameter shall be 30mm with a centre hole to allow M12 / M16 Bolt (as per schedule of prices) to pass through.

3.11 Dimensions and Tolerances

The dimensional tolerances of the bolts, nuts , screw threads and washers shall be in accordance with ISO 965 – 1980, 262-2 and 4759 1991.

3.12 Galvanizing

The boils, nuts and washers shall be hot dip galvanized to comply with BS 729 after all machining operations are completed.

Threads of bolts shall be spun galvanized and the threads of the nuts shall be oiled. The weight and thickness of zinc coating on the plain surfaces shall not be less than 610gm per square metre and 0.086mm respectively. The threaded portion shall have a minimum coating of weight not less than 305 gm of zinc per square metre and 0.086mm respectively. The threaded portion shall have a minimum coating of weight not less than 305 gm of zinc per square metre.

Preparation of galvanizing and the galvanizing itself shall not adversely affect the mechanical properties of the coated material.

To prevent the formation of white rust, all items shall be treated with sodium dichromate after galvanizing and stored under will ventilated conditions. Sheradising or other process shall not be used.

3.13 Finish

The bolts & nuts and washers shall be free from blister, scale, rust and other defects before galvanizing. The bolts, nuts and washers shall be smooth, clean, uniform throughout without any burs / sharp edges and free from defects after galvanizing. Washers shall be free from spelter after galvanizing.

The nuts shall be finger tight on bolts and will be rejected if they are excessively loose or tight fit. Bolts with threads re-died after galvanizing will also be rejected.

4.0 QUALITY ASSURANCE

The manufacturer shall have obtained Quality Assurance Certification conforming to ISO 9002 for the manufacture of galvanizing bolts and nuts / washers. Bidders shall furnish documentary evidence to prove this with the offer.

5.0 ADDITIONAL REQUIREMENTS

5.1 Marking

The following marking shall be embossed on the bolt head (top) during head forging operation and galvanizing shall not obliterate the marking.

a) Manufacturer's identification marks
b) The letters CEB
c) Property Class as per Table 3 of ISO 898 – 1

The diameter of the bolt as per ISO 261.

The property class of the nuts shall be marked as per ISO 898 – 2.

5.2 Packing

Each size of bolts with nuts / washers shall be packed separately in a polythene lined wooden boxes. Minimum number of bolts with nuts in a box shall be 100 and that of washers shall be 500. Each box shall be clearly marked with the following information.

a) Name of Manufacturer and Country of manufacture
b) Size of Bolt with Nut / Washer
c) Quantity
d) Gross Weight

6.0 INFORMATION TO BE PROVIDED WITH THE OFFER

The following particulars shall be furnished with the offer

a) Constructional features such as;

i) Grade of steel used for;

1) Bolts
2) Nuts
3) Washers

ii) Method of forming the;

1) Hexagonal head
2) Threads
3) Markings

iii) Method of galvanizing the

1) Bolts
2) Nuts
3) Washers

b) Particulars of Plants and Equipment available such as;

i) Name of the equipment
ii) Type of operation to be performed by the equipment
iii) Production rate (Number of components per hour)
iv) Number of equipment available

c) Dimensional drawings of Bolts, Nuts and Washers

d) Completed Schedule of Particulars, Annex – A

e) Certificate of Quality Assurance as per ISO 9002

f) Certificate of Type tests conforming to the relevant ISO specified on the following for each size;

i) Tensile Strength
ii) Vickers hardness
iii) Brinell hardness
iv) Rockwell hardness
v) Lower yield stress
vi) Stress under proofing load S_p/R_{el} N/mm^2
vii) Elongation after fracture
viii) Impact strength
ix) Head soundness

Test Certificate of the Type Tests performed shall conform to the standards specified.

The test certificates shall clearly identify the item concerned showing the Manufacturer's identity, types number and basic technical parameters and shall be issued by a **Recognized Independent Testing Authority acceptable to the purchaser.**

Failure to furnish the above particulars a will result in the offer being rejected.

7.0 SAMPLES

Two non-refundable samples of each size of bolts & nuts, flat washers and spring washers offered shall accompany the Bid to facilitate analysis and evaluation. While analyzing samples, the purchaser reserves the right to check dimensions, inspect workmanship, and perform tests as prescribed in relevant standards specified.

8.0 INSPECTION AND TESTING

8.1 Inspection

The selected Bidder shall make necessary arrangements for inspection by an Engineer appointed by the Purchaser and to carry out in his presence necessary Sample/acceptance tests of the bolts, nuts and washers offered in compliance with the standard specified at the place of manufacture.

8.2 Testing (Sample/Acceptance)

The following Sample / Acceptance test as per ISO 898 shall be witnessed by the Engineer for bolts, nuts and washers.

i) Dimensional Check
ii) Ultimate Tensile Strength
iii) Elongation after fracture
iv) Galvanizing Test

8.3 Sampling

The bolts & nuts/ washers packed as per Clause 5.2 shall be stored in such a manner to carry out sampling.

One bolt out of every 500 bolts of each size shall be selected randomly to carry out the acceptance tests as per Clause 8.2.

9.0 ANNEXURE

A - Schedule of Particulars – To be filled By the Bidder

ANNEX – A

SCHEDULE OF PARTICULARS

(To be filled by the Bidder for each size)

1)	Name of Manufacturer			-
2)	Country of origin			-
3)	Applicable Standards			-
	i) Bolts			-
	ii) Nuts			-
	iii) Flat Washers			-
	iv) Spring Washers			-
4)	Bolts			
	i)	Property Class		-
	ii)	Tensile Strength	Nominal Minimum	- -
	iii)	Vickers hardness	Minimum Maximum	- -
	iv)	Brinell hardness	Minimum Maximum	- -
	v)	Rockwell hardness	Minimum Maximum	- -
	vi)	Lower yield stress	Nominal	-
	vii)	Stress under proofing load	S_p/R_{el} N/mm^2	-
	viii)	Elongation after fracture	Minimum	-
	ix)	Impact strength	Minimum	-
	x)	Head soundness		-
5)	Nut			
	i)	Height of nut		-
	ii)	Width across flats		-
	iii)	Property Class		-

vi)	Vickers hardness	Minimum Maximum	- -
vii)	Brinell hardness	Minimum Maximum	- -
viii)	Rockwell hardness	Minimum Maximum	- -
ix)	Lower yield stress	Nominal	-
x)	Stress under Proofing load	S_p/R_{el} N/mm^2	-
xi)	Impact strength	Minimum	-

6) Constructional features

- i) Method of forming the hexagonal head -
- ii) Method of forming the threads -
- iii) Method of galvanizing -
  - a) Galvanizing coating thickness on plain surface
    - Bolt -
    - Nut -
    - Plain Washer -
    - Spring washer -
  - b) Galvanizing coating weight on plain surface
    - Bolt -
    - Nut -
    - Plain Washer -
    - Spring washer -
- iv) Method of marking -

7) Particulars of Plants and Equipment available at the place of Manufacture (attach separate sheet)

- i) Name of the equipment -
- ii) Type of operation to be performed by the equipment -
- iii) Production rate (Number of components per hour) -
- iv) Number of equipment available -

8) Particulars of testing equipment available at the place of manufacture (attach separate sheet) -

9)	Whether the relevant dimensional drawings are provided for;			
	i)	Bolts & Nuts	yes/no	-
	ii)	Flat Washers	yes/no	-
	iii)	Spring Washers	yes/no	-
10)	Whether the Type Test Certificate for the following are provided From recognized independent testing authority			
	i)	Tensile Strength	yes/no	-
	ii)	Vickers hardness	yes/no	-
	iii)	Brinell hardness	yes/no	-
	iv)	Rockwell hardness	yes/no	-
	v)	Lower yield stress	yes/no	-
	vi)	Stress under proofing load	S_p/R_{el} N/mm^2	-
	xii)	Elongation after fracture	yes/no	-
	xiii)	Impact strength	yes/no	-
	xiv)	Head soundness	yes/no	-
11.	Whether the specified samples (Ref Clause 7.0) furnished Yes/No			-
12.	Whether the manufacturer will carryout Acceptance / Sample test as per clause 8.3 at the place of manufacture during inspection		Yes/No	-
13.	Packing details			-
14.	Marking details			-

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SEAL AND SIGNATURE OF THE MANUFACTURER

DATE ....

ngalboin